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Measurement of surface topographies in the nm-range for power chip technologies by a modified low-coherence interferometer

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ABSTRACT

This work introduces a modified low-coherence interferometry approach for nanometer surface-profilometry. The key component of the interferometer is an element with known dispersion which defines the measurement range as well as the resolution. This dispersive element delivers a controlled phase variation which can be detected in the spectral domain and used to reconstruct height differences on a sample. In the chosen setup, both axial resolution and measurement range are tunable by the choice of the dispersive element.

The basic working principle was demonstrated by a laboratory setup equipped with a supercontinuum light source ($\Delta\lambda = 400 - 1700$ nm). Initial experiments were carried out to characterize steps of 101 nm on a silicon height standard. The results showed that the system delivers an accuracy of about 11.8 nm. These measurements also served as a calibration for the second set of measurements. The second experiment consisted of the measurement of the bevel of a silicon wafer. The modified low-coherence interferometer could be utilized to reproduce the slope on the edge within the previously estimated accuracy. The main advantage of the proposed measurement approach is the possibility to collect data without the need for mechanically moving parts.

Keywords: optical metrology, interferometric measurement, dispersion based measurements, in-line characterization, low-coherence interferometry, surface profilometry

1. INTRODUCTION

As approximately 50 % of electrical energy is lost from the generation during multiple conversions to the end application, power electronics still bear great potential, [1]. Above all, new manufacturing technologies in semiconductors can help to make use of this potential. Essential parameters in the production of power semiconductors are the productive area on a wafer and the number of chips which can be produced flawlessly, also known as yield. The recent introduction of 300 mm wafers in this sector has positively contributed to both parameters, [2]. Where the number of chips per wafer increased by a factor of 2.5, other problems in handling and manufacturing arose. In contrast to CMOS processes, where 300 mm wafers are rather standard, power semiconductors have completely different production processes. Power semiconductors use nearly the entire silicon volume of the wafer as the current in structures like MOSFETs flows vertically. In order to increase the efficiency, manage the heat and decrease the resistance in power transistors wafers are thinned as much as possible, [1]. While standard 200 mm processes use 70 μm thin wafers, the 300 mm technology relies on 20 - 40 μm thinned substrates, [3]. Furthermore, power semiconductors rely on more complex process steps. Structures need processing not only on the front- and backside but also in a vertical manner. Additionally, high temperature treatments (up to 1200 °C) and the wafer thinning are crucial. These overall conditions lead to the necessity for specialized tools for the

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challenging handling and processing of the thinned wafers. While handling is delicate, small process variations in polishing or positioning can have a huge influence on the manufacturing of important features. Especially, unwanted deviations on parameters like the surface roughness and topography can cause major problems in processes such as lithography. In order to increase the yield and use all advantages of the 300 mm technology, precise and process-accompanying metrology is required, [4, 5]. The main demands for tools to measure surface features are nm-axial resolution, μm-lateral resolution and the possibility to perform measurements on production structures during the process. One key aspect in the characterization of production wafers in opposition to test samples is the possibility to measure on a wide range of materials and surface compositions. Especially the characterization of multiple layered chips and high aspect ratios are demanding for existing metrology. Tools like atomic force microscopy (AFM) perform well in terms of axial and lateral resolution, [6]. They have been shown to be excellent tools in laboratory environments for applications such as microbiology and nano-structured materials [7–9]. However, AFM measurements over areas larger than the standard (5 x 5 μm) require special installations and measurement times increase significantly, [10].

A second common measurement technology in the semiconductor industry is so-called scatterometry which retrieves surface profile information based on reflected intensities, [11–13]. The technique relies on the reflection on periodic surface structures where a well-known model of the materials and the structures involved enable nm-precise measurements, [14,15]. These requirements limit its flexibility and the use as an in-line tool. Furthermore, metrology approaches such as confocal laser scanning microscopy [16] and scanning white-light interferometry [17] have shown the appropriate accuracy. As these technologies deliver a good performance on a lab scale with appropriate test samples they are not applicable to situations in a production environment with more complex samples due to speed issues, [18].

Within this work, an alternative approach based on low-coherence interferometry (LCI) is proposed, implemented and tested. This approach aims to be both precise in the nm-range regarding surface profiles, and adaptable to be integrated into a production machine or line.

2. EXPERIMENTAL APPROACH

In order to achieve the goal of an nm-precise surface profilometer, a modified low-coherence interferometer is utilized, [19]. The Michelson interferometer is powered by a supercontinuum light source ($\Delta\lambda = 400 - 1700$ nm, ilum 1, Fiberware GmbH, Germany) and uses an imaging spectrometer in order to resolve spectral information along one spatial dimension, Fig. 1. Both arms are fixed where one arm contains a reference mirror and an

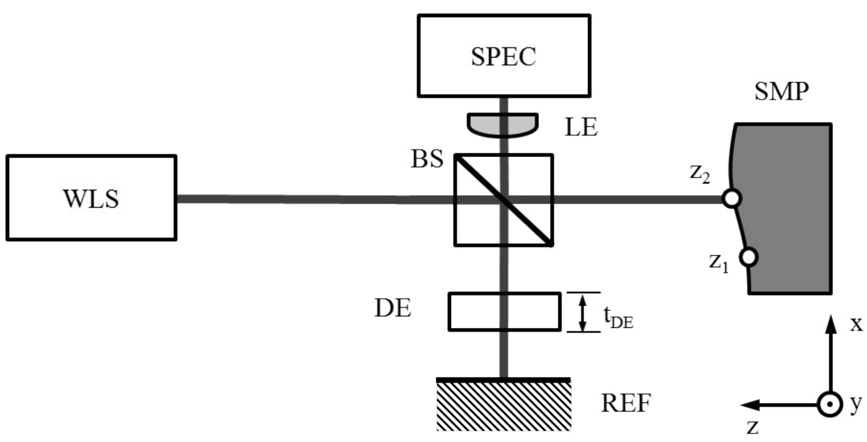

Figure 1. a) Experimental setup with WLS - white-light source, BS - beam splitter, SMP - sample (i.e. wafer) where z_1 and z_2 are two different heights, REF - fixed reference mirror, DE - dispersive element with the thickness t_{DE}, LE - lens to image the sample on the spectrometer, SPEC - imaging spectrometer

element of known dispersion (Schott N-BK7, $t_{DE} = 2000$ μm). The second arm is formed with the sample's surface as reflective element. The sample consists of different heights along the x-y-plane $z_i(x, y)$. The output signal at the spectrometer can be described by using common two-beam interferometer equations [20] under the consideration of the dispersion in the system [21]:

$$I(\lambda) = I_0(\lambda) \cdot (1 + \cos\phi(\lambda)) \tag{1}$$

$$\phi(\lambda) = 2\pi \frac{(n(\lambda)-1)t_{DE} - \delta}{\lambda} \tag{2}$$

where $I_0(\lambda)$ is the initial spectral intensity before the beam splitter and $\phi(\lambda)$ is the absolute phase of the signal which is dependent on the optical path difference (OPD) between both arms denoted with δ and the wavelength λ. The introduced dispersion due to the wavelength dependent refractive index $n(\lambda)$ and the material's thickness t_{DE} transforms the initial interference signal. The periodicity of fringes tends to a minimum, the so-called equalization wavelength λ_{eq}, which is dependent of the OPD, Fig. 2.

When using the interferometer as a profilometer, every height change in the sample's surfaces (e.g. z_1 and z_2)

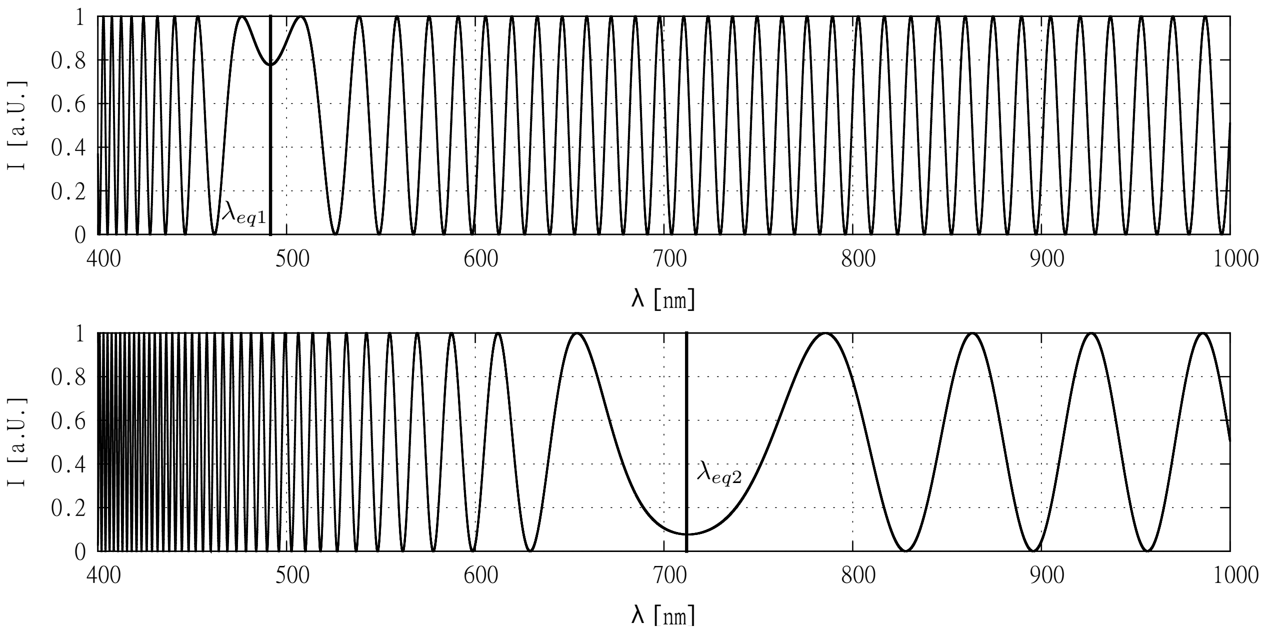

Figure 2. Schematic representation of an intensity signal where the samples surface at two independent points (e.g. z_1 and z_2) shows two different equalization wavelengths λ_{eq1} and λ_{eq2}

changes the path length δ. This therefore leads to a different equalization wavelength (e.g. λ_{eq1} and λ_{eq2}) which can be easily measured with the spectrometer. The equalization wavelength can be found by calculating the zero of the derivative of the phase signal:

$$\left(\frac{\partial\phi}{\partial\lambda}\right)_{\lambda_{eq}} = 0 \tag{3}$$

The relative or absolute height z at a given point $P(x, y)$ can be calculated by fitting the recorded spectrum and determining the equalization wavelength which will lead to a certain path length δ. The choice of the dispersive element determines the measurement range Δz

$$\Delta z(\lambda) = n_{group}(\lambda) \cdot (t_{DE}/2) \tag{4}$$

where $n_{group}(\lambda)$ is the group refractive index of the element's material. Furthermore, it determines the resolution in combination with the used spectral range of the light source, the spectrometer and the quality of the fitting routine.

3. RESULTS

The evaluation of the proposed setup was performed in two steps. In the first experiment a height reference standard was measured with the modified low-coherence approach to characterize the performance of the setup. A second experiment consisted of measurements on the bevel of a wafer conducted with the low-coherence interferometer.

A silicon substrate with different step structures served as a height standard (Simetrics VS, Simetrics GmbH, Germany). The structures have a nominal height of 101 nm and were calibrated against a PTB standard 2002-0004. An initial equalization wavelength of 560 nm was adjusted for the first measurement on the top of the structure. In all following measurements, the equalization wavelength was determined by a least-squares fit procedure following equations (1)-(3). The surface profile was then calculated relative to the top level, Fig. 3. The

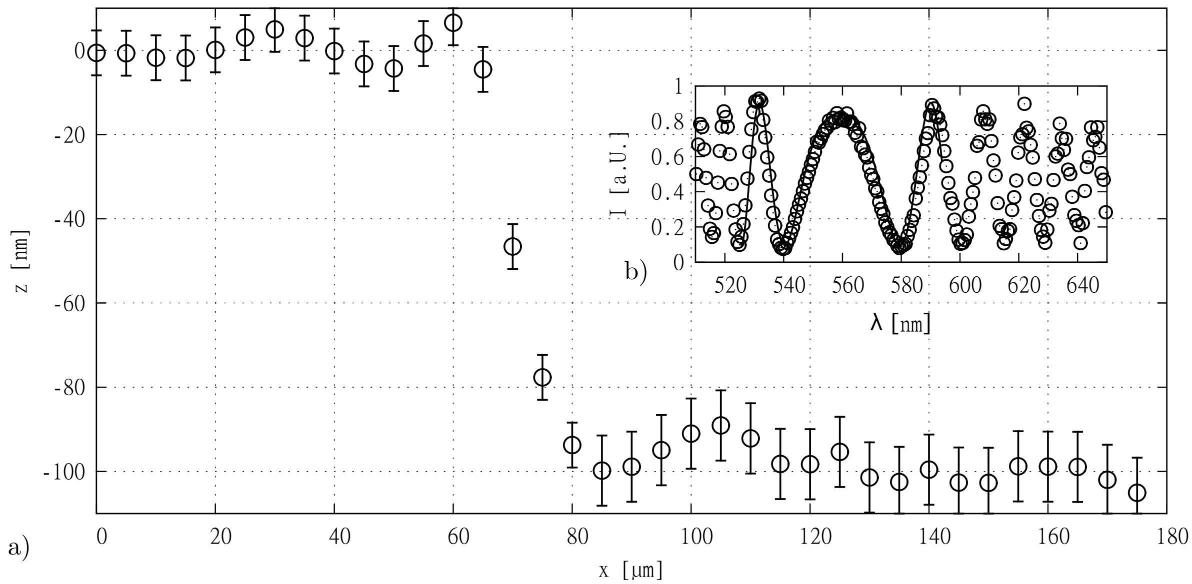

Figure 3. Results of the first experiment with a) measured line profile of the step height standard with a nominal height of $z_{nom} = 101$ nm where the error is plotted as the 95% confidence and b) one sample spectrum plotted as circles and fitted curve plotted as a solid line

obtained data shows a slight tilt of the profile with a value of 1.2 $nm/\mu m$ which was corrected mathematically. It is visible that the 101 nm step can be reproduced with only minor deviations. The measured mean value of the step was $\bar{z} = 98.4$ nm with a standard deviation of $z_\sigma = 4.2$ nm. Furthermore, the RMS error relative to the nominal step height of 101 nm quoted by the standard's manufacturer is $z_\epsilon = 11.8$ nm. The recorded deviations are also inside the confidence band of ± 10 nm given by the manufacturer. The data shows that the low-coherence interferometer is able to reproduce the steep edge although some minor deviations occur in this area of the sample. The reason for these deviations can be found in a reduced signal-to-noise ratio due to scattering effects which increase the fitting error for data sets in this area. Additional investigations in order to improve the measurement of steep edges are underway.

The second measurement was performed on a silicon wafer with 200 mm diameter (Infineon Technologies Dresden GmbH, Germany). The measurements with the low-coherence interferometer have been conducted in a comparable manner to the first experiment. An initial equalization wavelength of 560 nm was adjusted for the flat part of the wafer. All data taken within this measurement were fitted using the above-mentioned algorithm. Afterwards, the surface profile was calculated relative to the start level, Fig. 4. It is visible in the analyzed data that the low-coherence interferometer reproduces the slope of the wafer bevel well. Over the course of 300 μm a relative height change of 350 nm was recorded. The data has been taken in a section of the slope where the height changes gradually in order to avoid edge effects which might introduce further error as shown in the first experiment (compare Fig. 3).

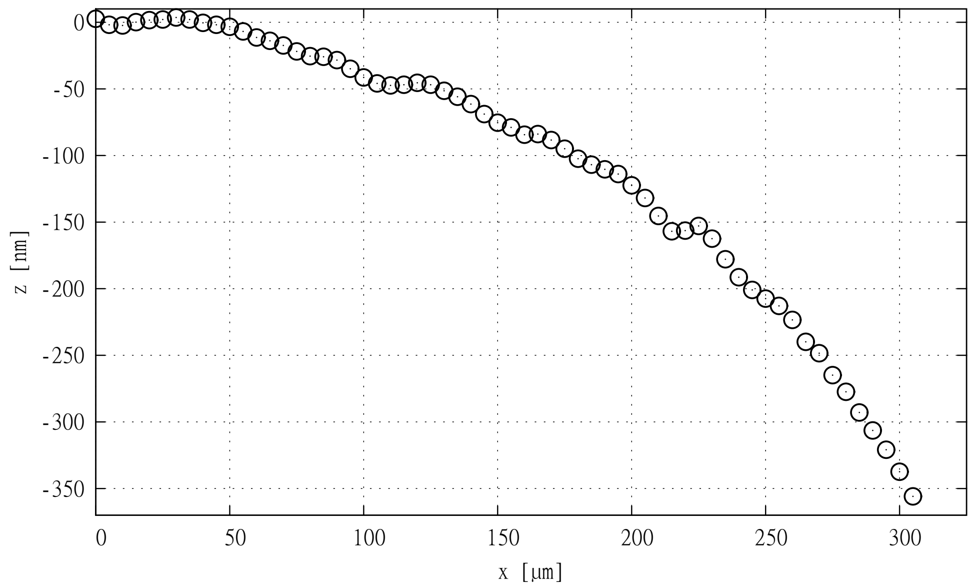

Figure 4. Results of the wafer bevel characterization with the low-coherence interferometer measurement in circles where the height level z decreases with the radial position on the wafer in x-direction

4. CONCLUSION AND OUTLOOK

An alternative approach to surface profilometry based on a modified low-coherence interferometer was presented within this work. The interferometer records spectra with distinct phase minima which occur due to a known dispersion in the system and an optical path length difference caused by a surface profile of the sample.

Experiments on a silicon surface height standard showed that the system can resolve a step of 101 nm with an accuracy of 11.8 nm. The results showed diffraction effects due to the steep change in height at the edge. This leads to some error of the values close to the edge. This source of error as well as chromatic aberrations and uncertainties in the fitting routine are subject to further developments to improve the system. This result made clear that the desired accuracy is possible with this approach so that measurements on a semiconductor production wafer could be performed.

For that purpose, the bevel of a wafer was investigated with the developed setup. It was obvious in the results that the distinctive slope of the wafer bevel with height differences of 350 nm along a distance of 300 μm could be characterized. It is desired to further analyze the end of the wafer bevel with its sharp edge corner after the planned system optimization. In comparison to other technologies, the low-coherence interferometer approach enables faster measurements. The approach does not have a need for mechnical stepping in the height range. This advantage makes it suitable for in-line measurements in the production of power semiconductors. Additionally, the LCI enables measurements of comparatively large height ranges with high resolution.

Further development will be done to improve the mechanical and temperature stability of the setup. Initial tests regarding the in-line operation on 300 mm wafers in a semiconductor fab have already been performed. The analyzing algorithm as well as the computer hardware also show room for improvement regarding speed and reliability in an in-line application. Additional experiments to evaluate the measurement performance on multi-layered and multi-material wafers are planned as well.

In conclusion, the proposed experimental approached showed high potential for a new, reliable and precise in-line surface profilometer technique.

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